The Futures of Particle Physics

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Fermilab

Particle Accelerator Conference

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From the 1898–99 University of Chicago catalogue:

"While it is never safe to affirm that the future of the Physical Sciences has no marvels in store even more astonishing than those of the past, it seems probable that most of the grand underlying principles have been firmly established and that further advances are to be sought chiefly in the rigorous application of these principles to all the phenomena which come under our notice .... An eminent physicist has remarked that the future truths of Physical Science are to be looked for in the sixth place of decimals."

Our Picture of Matter

Pointlike ($r \lesssim 10^{-18}$ m) **quarks**

$$\begin{pmatrix} u \\ d \end{pmatrix}_L \qquad \begin{pmatrix} c \\ s \end{pmatrix}_L \qquad \begin{pmatrix} t \\ b \end{pmatrix}_L$$

and **leptons** (idealization that neutrinos are massless) ...

$$\begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_L \qquad \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix}_L \qquad \begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix}_L$$

with interactions specified by

$$\mathbf{SU(3)_c \otimes SU(2)_L \otimes U(1)_Y}$$

gauge symmetries ...

Elementarity

▷ Are quarks and leptons structureless?

Symmetry

▷ Electroweak symmetry breaking and the 1-TeV scale

▷ Origin of gauge symmetries

Unity

▷ Coupling constant unification

▷ Unification of quarks and leptons (new forces!); of constituents and force particles

▷ Incorporation of gravity

Identity

▷ Fermion masses and mixings; CP violation; neutrino oscillations

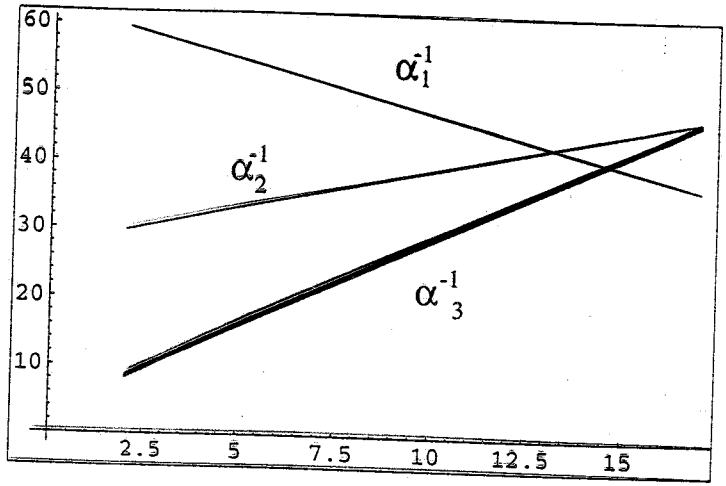
▷ What makes an electron an electron and a top quark a top quark?

Topography

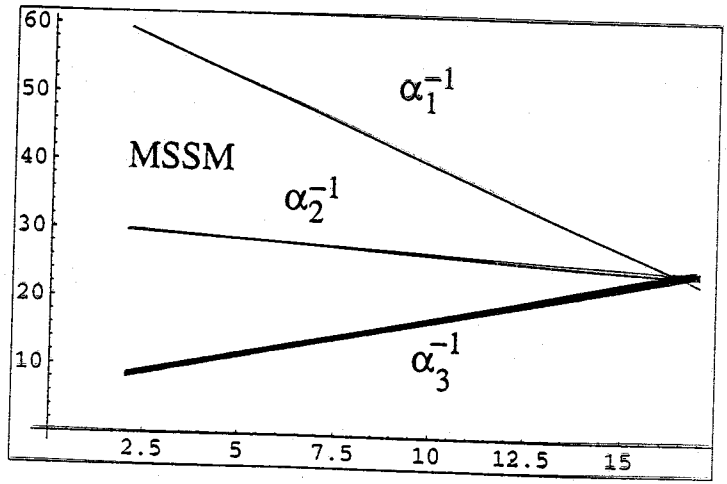
▷ What is the fabric of space and time?

SUSY GUTS

$$SU_C(3) \times SU_W(2) \times U_Y(1) \supset SU(5)$$



Log(E) (GeV)



Log(E) (GeV)

A Decade of Discovery Ahead

- ▷ Higgs search and study; elucidate electroweak symmetry breaking / 1-TeV scale.
- ▷ CP violation in the B system
- ▷ Rare decays (K, D, ...)
- ▷ ν oscillations
- ▷ Top as a tool
- ▷ New phases of matter
- ▷ Exploration!
  Extra dimensions / new dynamics / SUSY / new forces and constituents
- ▷ Proton decay
- ▷ What kinds of matter and energy make up the universe?
- ▷ Particle astrophysics and astronomy; precision cosmology; astroparticles

The decade of discovery won't happen automatically . . .

- ▷ Many of our goals are difficult.
- ▷ Timely success is in doubt for many experiments.
- ▷ Getting to the answers is important!

. . . and neither will the glorious future that lies beyond.

- ▷ We've done too little to prepare alternative futures.
- ▷ The scope of our science has grown; funding has not.
- ▷ We are communicating the wonders of our science inadequately.

Electroweak theory has many successes

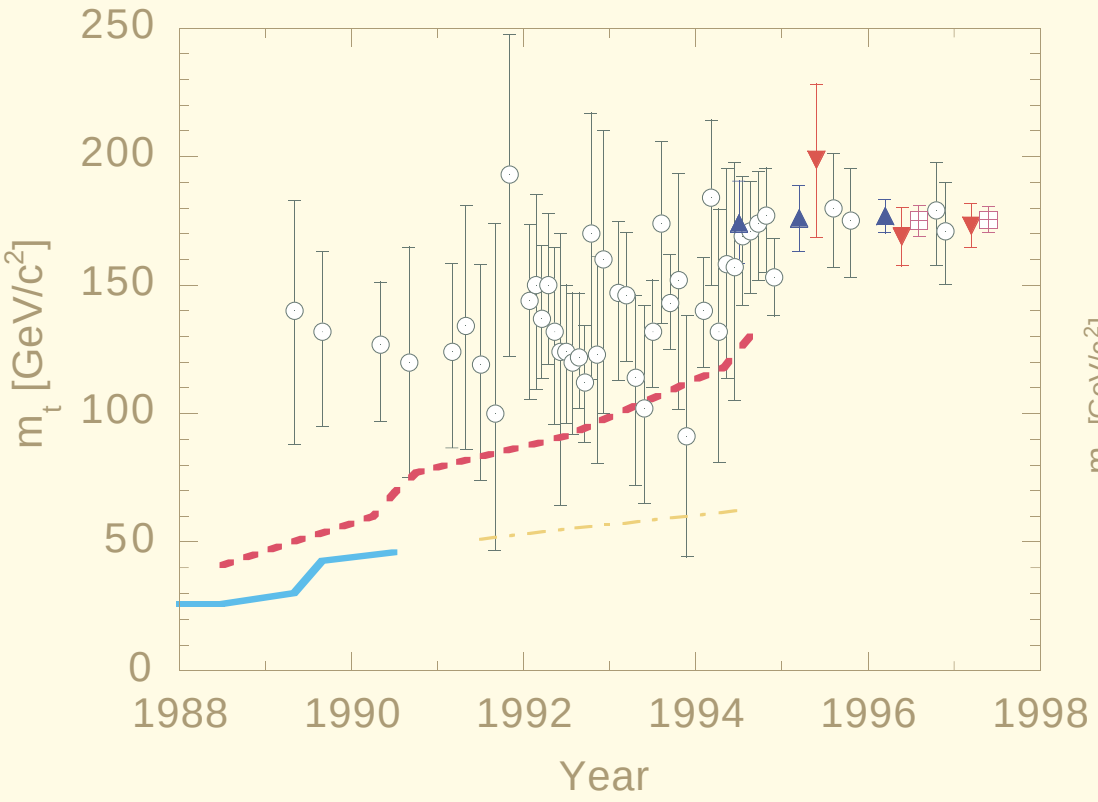
- Neutral currents
- Charm
- Weak gauge bosons $W^{\pm}$ and Z^0

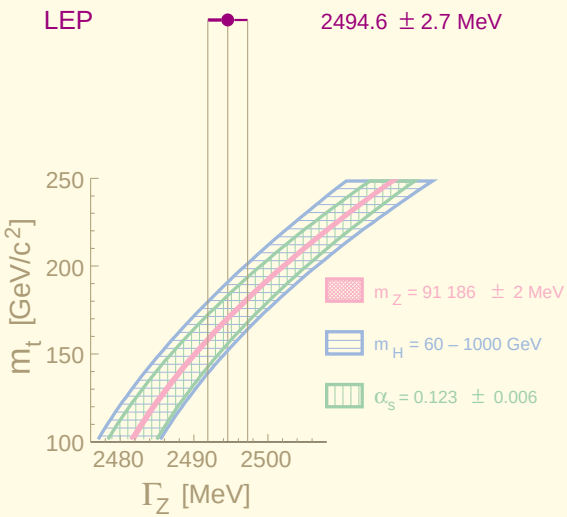
A decade of LEP, et al.

- Testing the quantum field theory at the one per mille level
- Looking for new physics "in the sixth place of the decimals"

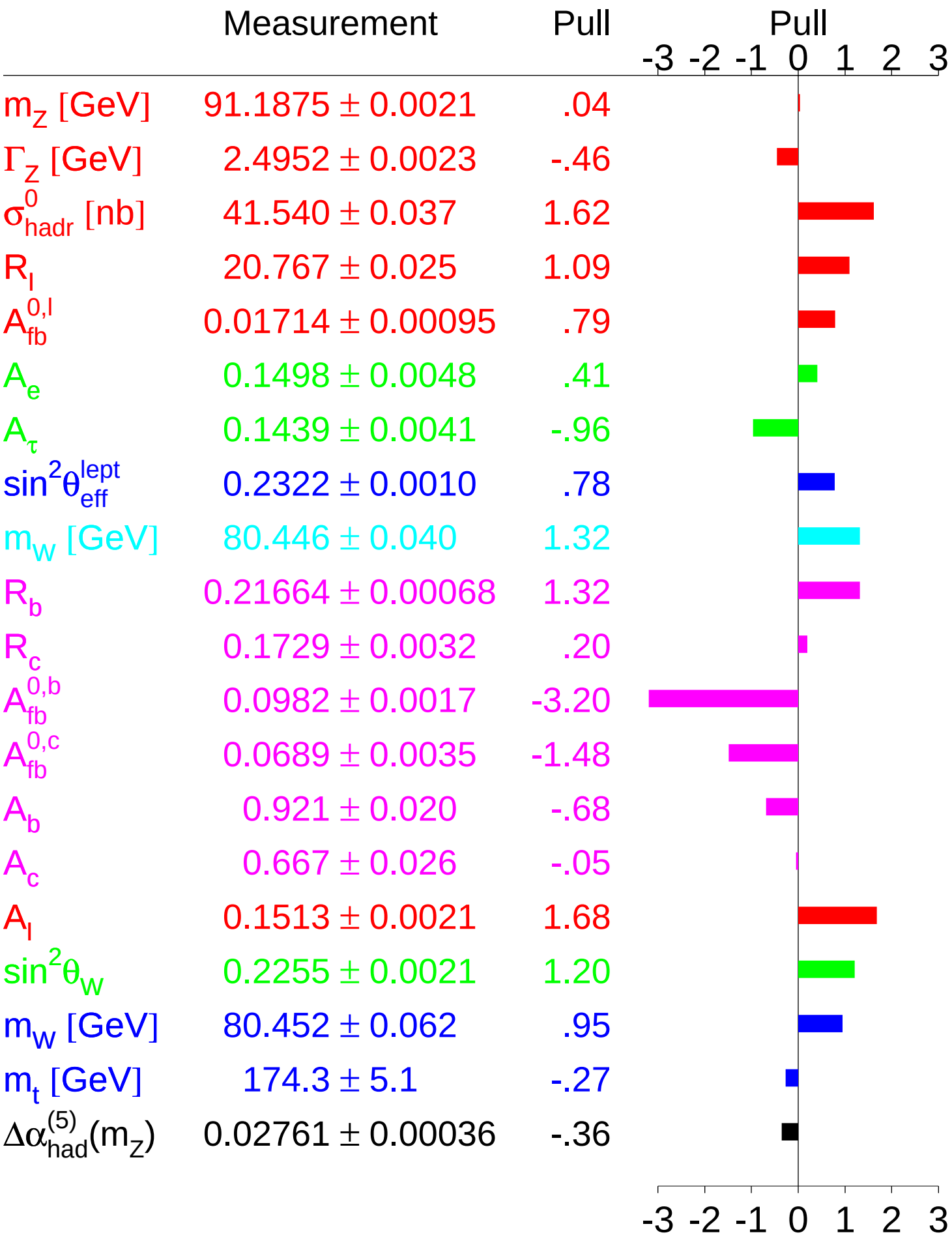
Precision measurements to determine unknown parameters . . .

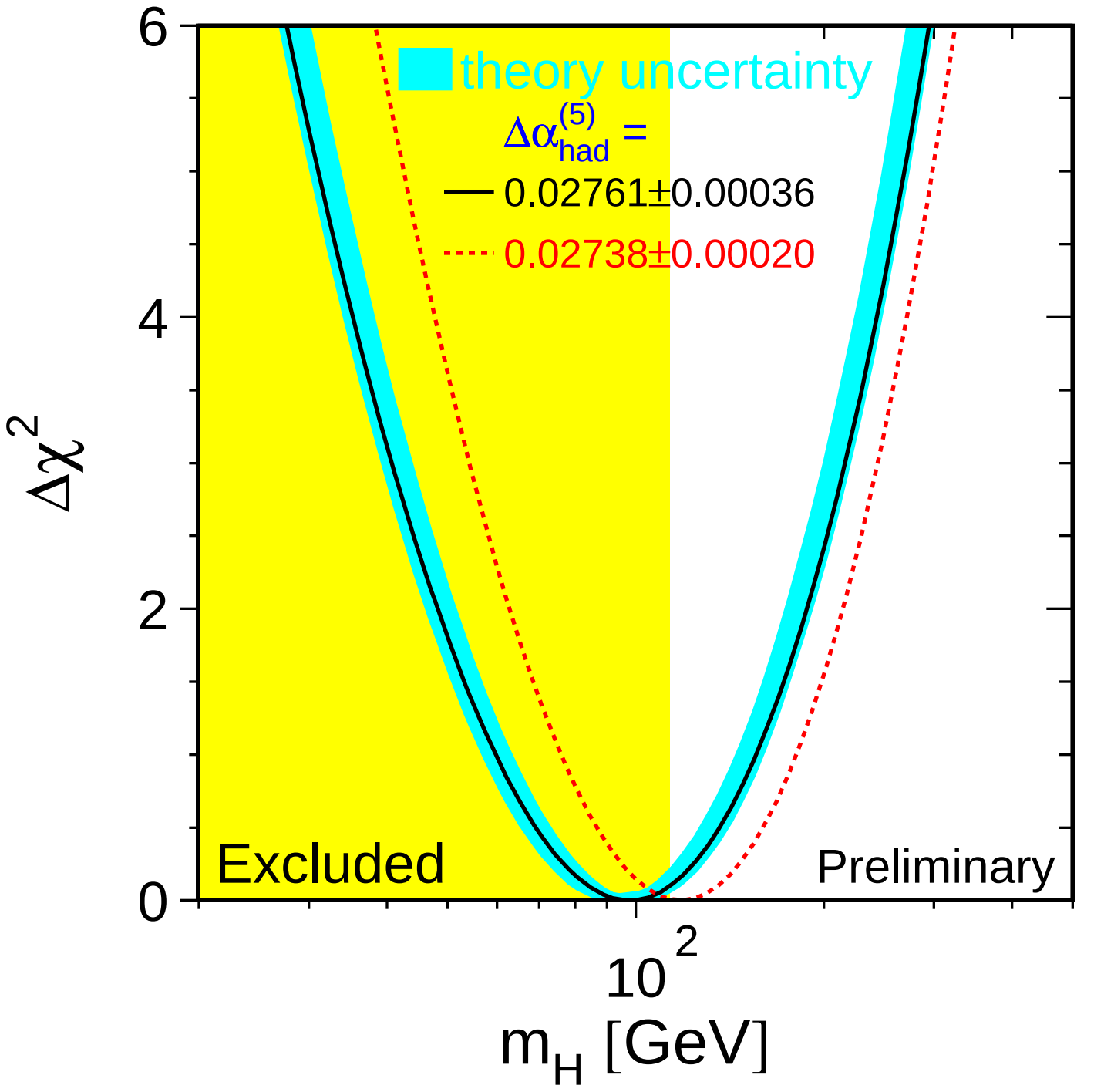
Inferring the top-quark mass through its rôle in quantum corrections:





Winter 2001


Measurement
Pull
Pull
-3 -2 -1 0 1 2 3
m_Z [GeV] 91.1875 ± 0.0021 .04
Γ_Z [GeV] 2.4952 ± 0.0023 -.46
σ^0_{hadr} [nb] 41.540 ± 0.037 1.62
R_l 20.767 ± 0.025 1.09
$A^{0,l}_{fb}$ 0.01714 ± 0.00095 .79
A_e 0.1498 ± 0.0048 .41
A_τ 0.1439 ± 0.0041 -.96
$\sin^2\theta^{lept}_{eff}$ 0.2322 ± 0.0010 .78
m_W [GeV] 80.446 ± 0.040 1.32
R_b 0.21664 ± 0.00068 1.32
R_c 0.1729 ± 0.0032 .20
$A^{0,b}_{fb}$ 0.0982 ± 0.0017 -3.20
$A^{0,c}_{fb}$ 0.0689 ± 0.0035 -1.48
A_b 0.921 ± 0.020 -.68
A_c 0.667 ± 0.026 -.05
A_l 0.1513 ± 0.0021 1.68
$\sin^2\theta_W$ 0.2255 ± 0.0021 1.20
m_W [GeV] 80.452 ± 0.062 .95
m_t [GeV] 174.3 ± 5.1 -.27
$\Delta\alpha^{(5)}_{had}(m_Z)$ 0.02761 ± 0.00036 -.36
-3 -2 -1 0 1 2 3


theory uncertainty
$\Delta\alpha^{(5)}_{had}$ =
0.02761±0.00036
0.02738±0.00020
Excluded
Preliminary
$\Delta\chi^2$
0
2
4
6
10^2
m_H [GeV]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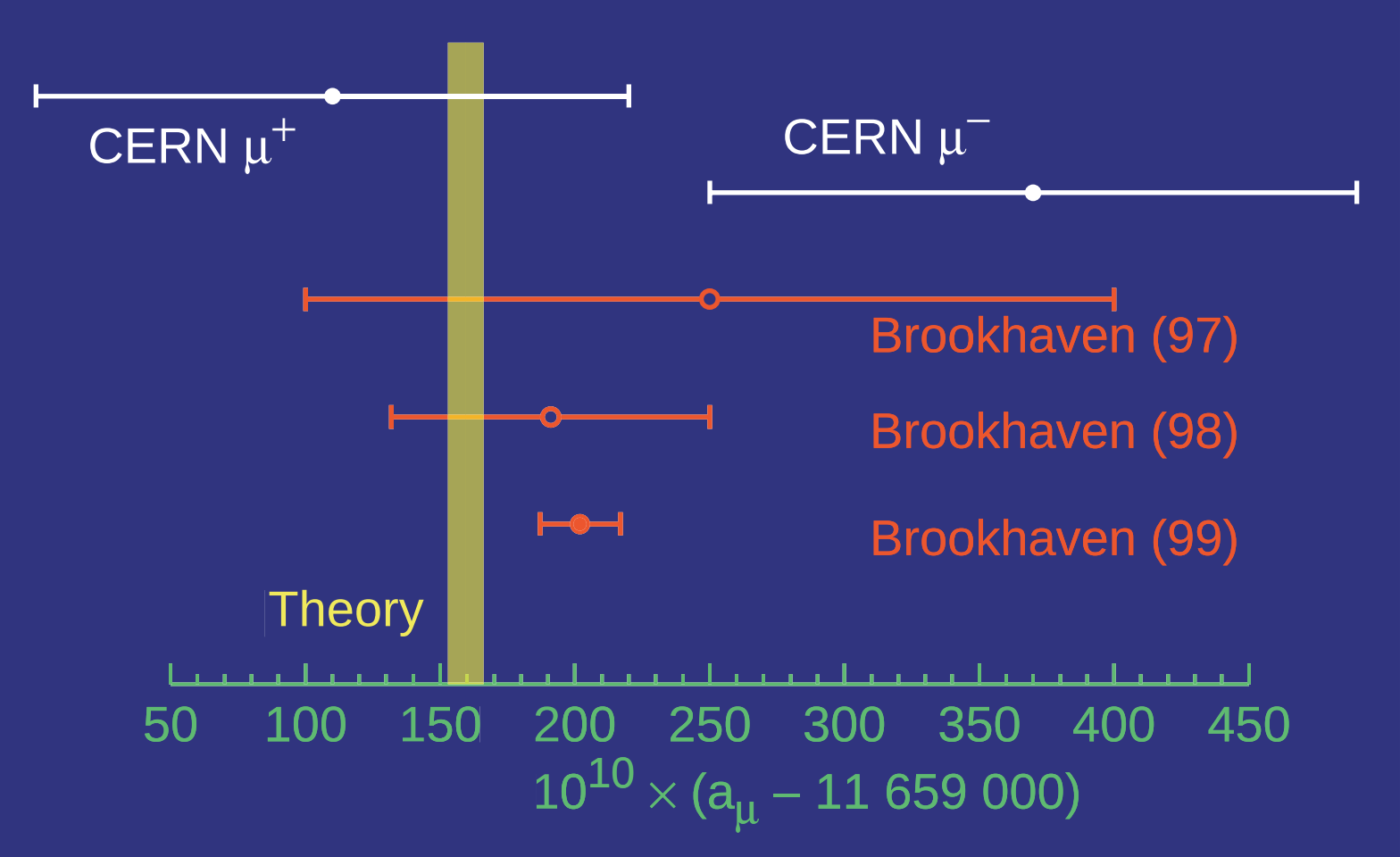

CERN μ^+
CERN μ^-
Brookhaven (97)
Brookhaven (98)
Brookhaven (99)
Theory
50
100
150
200
250
300
350
400
450
$10^{10} \times (a_\mu - 11\ 659\ 000)$

An outlier from atomic parity violation . . .

Bennett and Wieman (Boulder) determined the weak charge of Cesium by measuring the transition polarizability for the 6S-7S transition.

$$Q_W(\mathrm{Cs}) = -72.06 \pm 0.28\ (\mathrm{expt}) \pm 0.34\ (\mathrm{theory}):$$

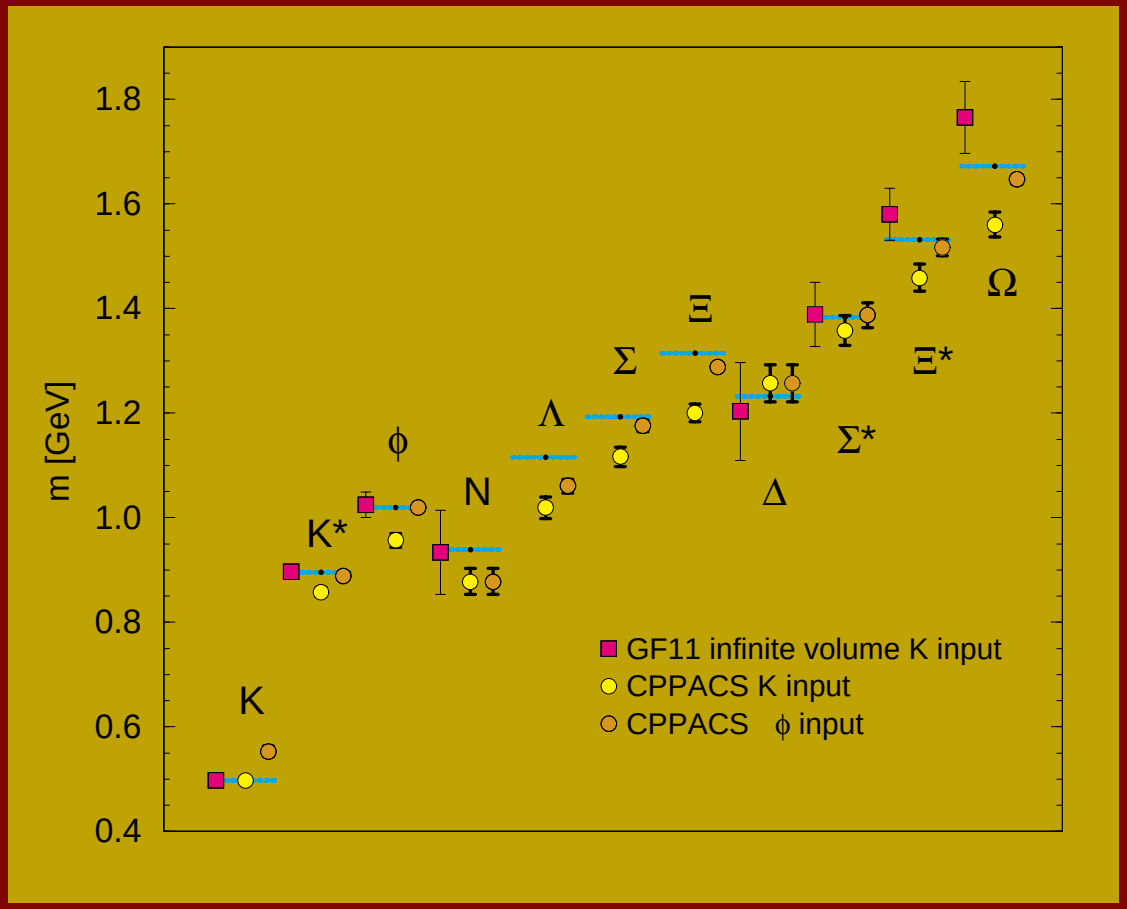
Experimental error $\times 1/7$; reduced theoretical uncertainty.

≈ 2.5 standard deviations above the electroweak theory.

Do the outliers contribute much-needed χ^2 . . .

. . . or signal cracks in the electroweak theory?

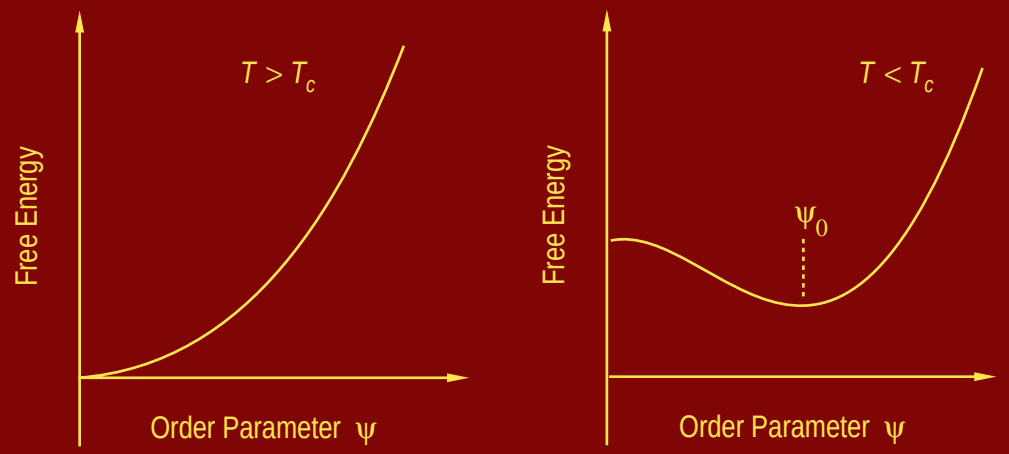
QCD explains the light hadron masses



For p, ρ, $[\pi]$, . . . , *confinement energy* is the source.

"Mass without mass"

Analogy to superconductivity sets M_W, M_Z



Meissner effect: EM fields disturb condensate of Cooper pairs

Weak bosons disturb Higgs condensate, acquire masses:

$$M_W^2 = \frac{g^2 v^2}{2} = \frac{\pi\alpha}{G_F\sqrt{2}\sin^2\theta_W}\ ; \quad M_Z^2 = \frac{M_W^2}{\cos^2\theta_W}$$

$$\text{EW scale is } v = \left(G_{\rm F}\sqrt{2}\right)^{-\frac{1}{2}} \approx 246 \text{ GeV}$$

A massive spin-zero particle must exist: "Higgs boson"

Disturbing EW condensate may generate fermion mass

EWSB is necessary, not sufficient

Standard model: each fermion mass $\Rightarrow$ new, *unknown* Yukawa coupling

$$\mathcal{L}^{(e)}_{\text{Yukawa}} = -\zeta_e \left[\overline{\mathsf{R}}(\phi^\dagger \mathsf{L}) + (\overline{\mathsf{L}}\phi)\mathsf{R}\right].$$

$$\boxed{m_e = \zeta_e v/\sqrt{2}}$$

All fermion masses $\sim$ physics beyond the standard model!

$$\zeta_t \approx 1 \qquad \zeta_e \approx 3 \times 10^{-6} \qquad \zeta_\nu \approx 10^{-10}\ ??$$

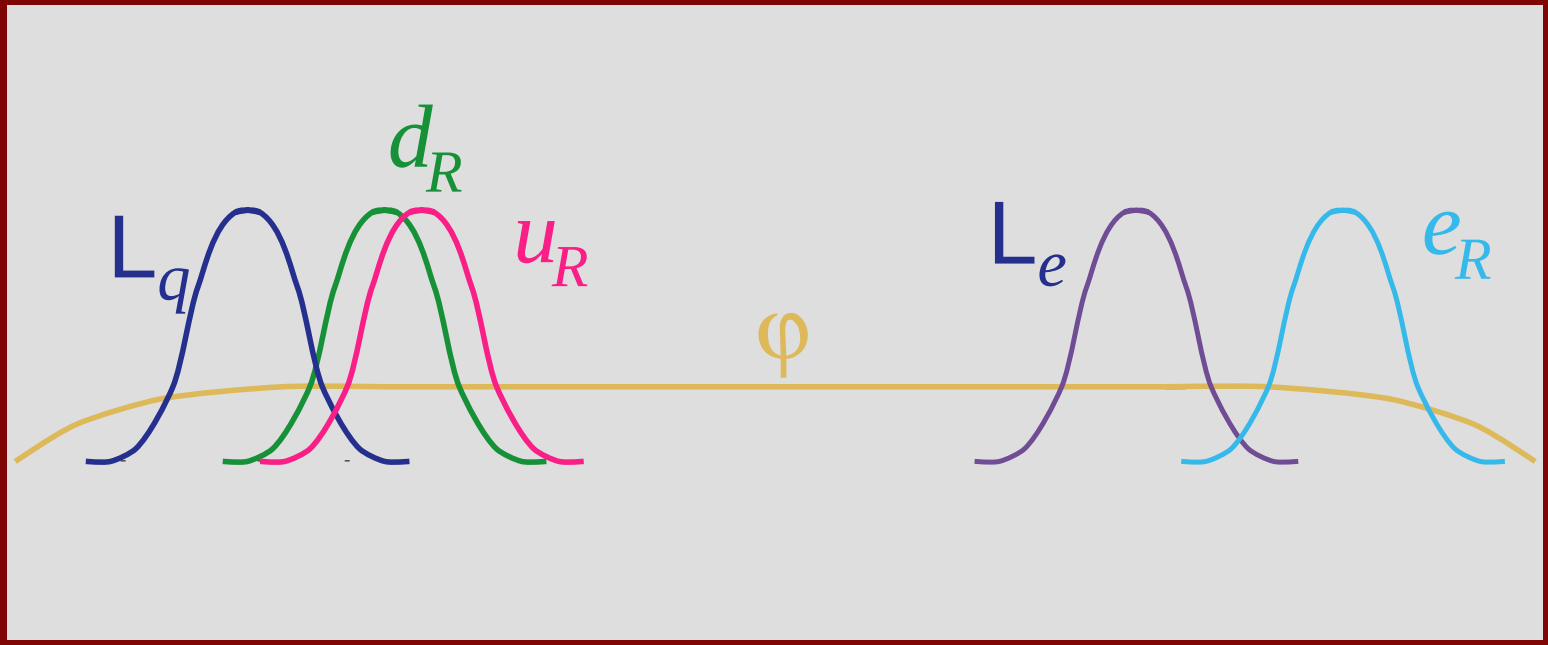
What accounts for the range and values of the Yukawa couplings?

There may be *other sources* of neutrino mass

Best hope until now:

Unified theories: pattern of fermion masses *simplifies* on high scales

Might Extra Dimensions Explain the Range of Fermion Masses?



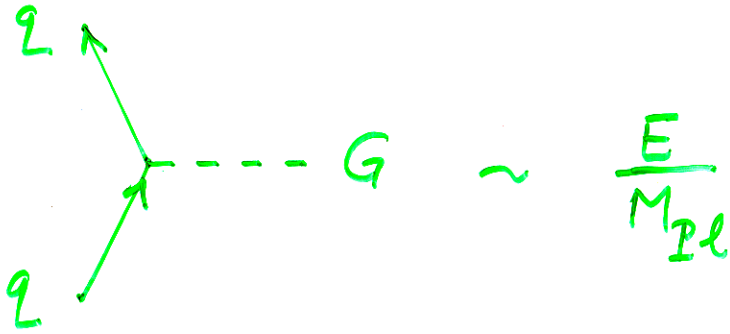
Arkani-Hamed, Schmaltz, and Mirabelli:

Different fermions ride different tracks in the 5^{th} dimension

Small offsets in the new coordinate $\Rightarrow$ exponential differences in masses

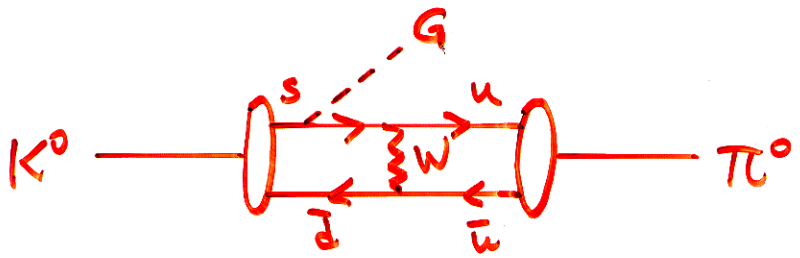
NATURAL TO NEGLECT GRAVITY IN PARTICLE PHYSICS:

G_N SMALL $\Leftrightarrow$ M_{Pl} LARGE



$G \sim \frac{E}{M_{Pl}}$

ESTIMATE $B(K \to \pi G) \sim \left(\frac{M_K}{M_{Pl}}\right)^2 \sim 10^{-38}$



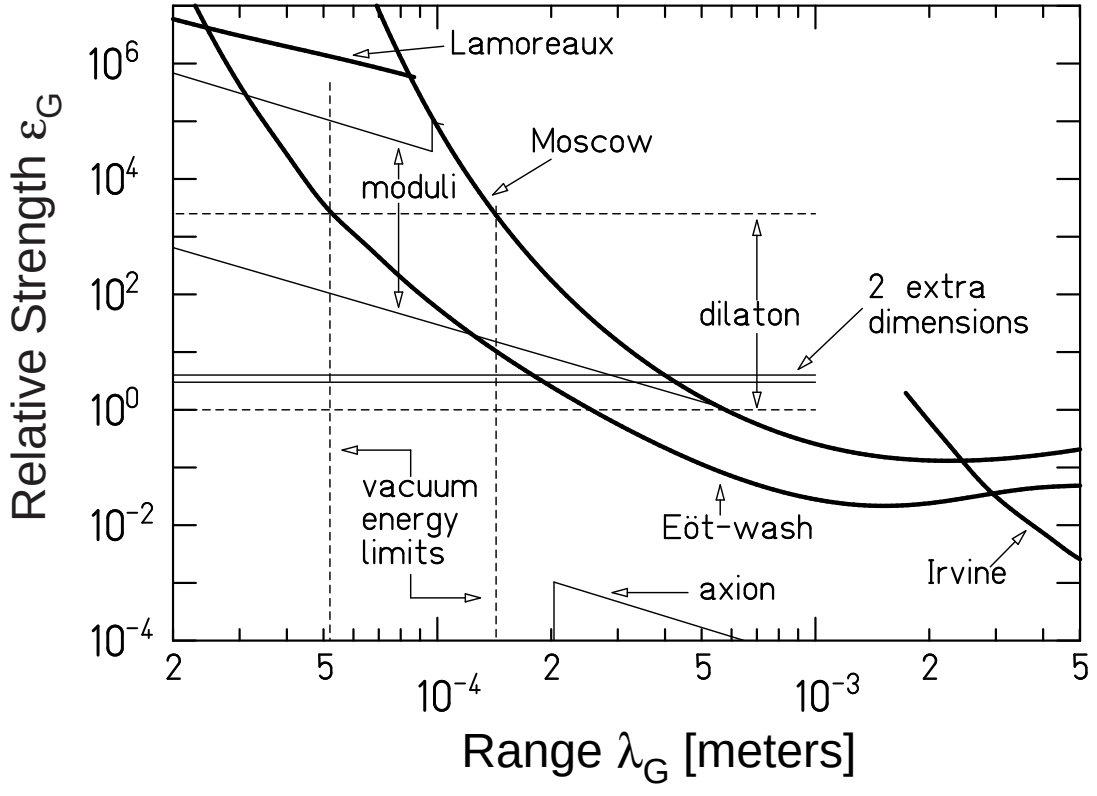
Newton + 300 yrs: Why is gravity weak?

NOVEL SPECULATION

Change Gravity to understand why $M_{Pl} \gg v$

STRING THEORY: EXTRA SPACE DIMENSIONS TRADITIONALLY ASSUMED $R_{ED} \leq 1/M_{Pl}$ $(10^{-35}\ m)$

EXPERIMENT: GRAVITY FOLLOWS NEWTONIAN FORCE LAW TO ~ 1 mm.


Relative Strength ε_G
10^6
10^4
10^2
10^0
10^{-2}
10^{-4}
Lamoreaux
Moscow
moduli
dilaton
2 extra dimensions
vacuum energy limits
Eöt-wash
Irvine
axion
2
5
10^{-4}
2
5
10^{-3}
2
5
Range λ_G [meters]

We know from EW theory alone that the 1-TeV scale is special:

$$M_H^2 < \frac{8\pi v^2}{3 G_F} = 1\ \text{TeV}^2$$ (Higgs boson or new physics)

CONVENTIONAL APPROACH TO UNDERSTAND

WHY $(M_H, v) \ll M_{Pl}$

(resolve hierarchy problem):

EXTEND THE STANDARD MODEL

$SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$ { composite Higgs (technicolor / topcolor), supersymmetry, ...

(effects on discrete symmetries)

IF GRAVITY PROPAGATES IN EXTRA DIM, dimensional analysis changes (Gauss)

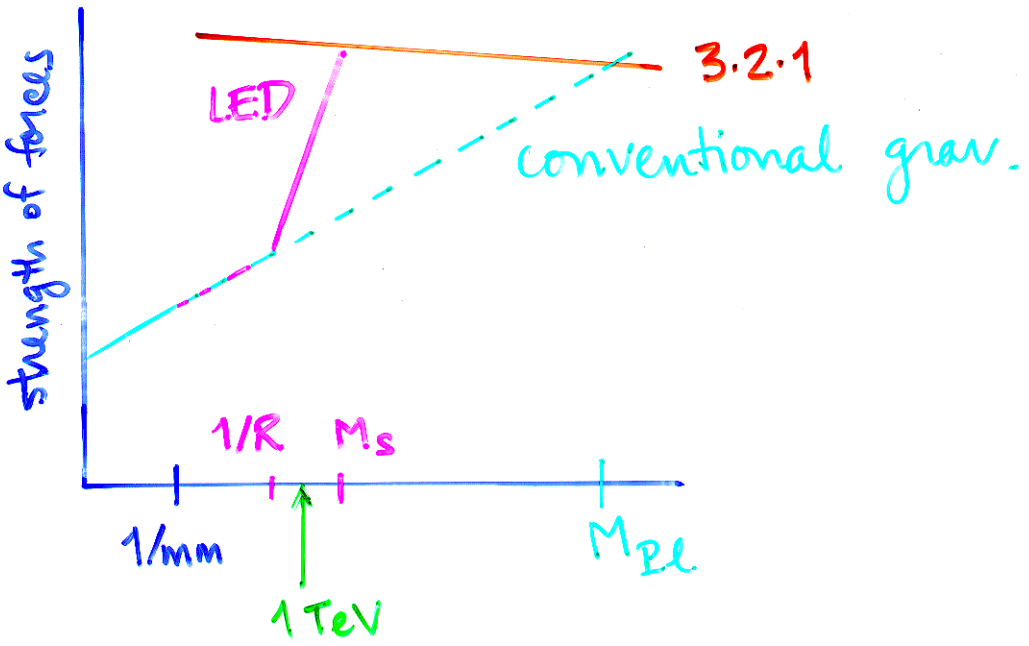
n extra dim., radius R $\Rightarrow$

$$G_N \sim M_{Pl}^{-2} \sim M_s^{-n-2} R^{-n}$$

If $M_s \sim 1$ TeV, $R \lesssim 1$ mm for $n \geq 2$

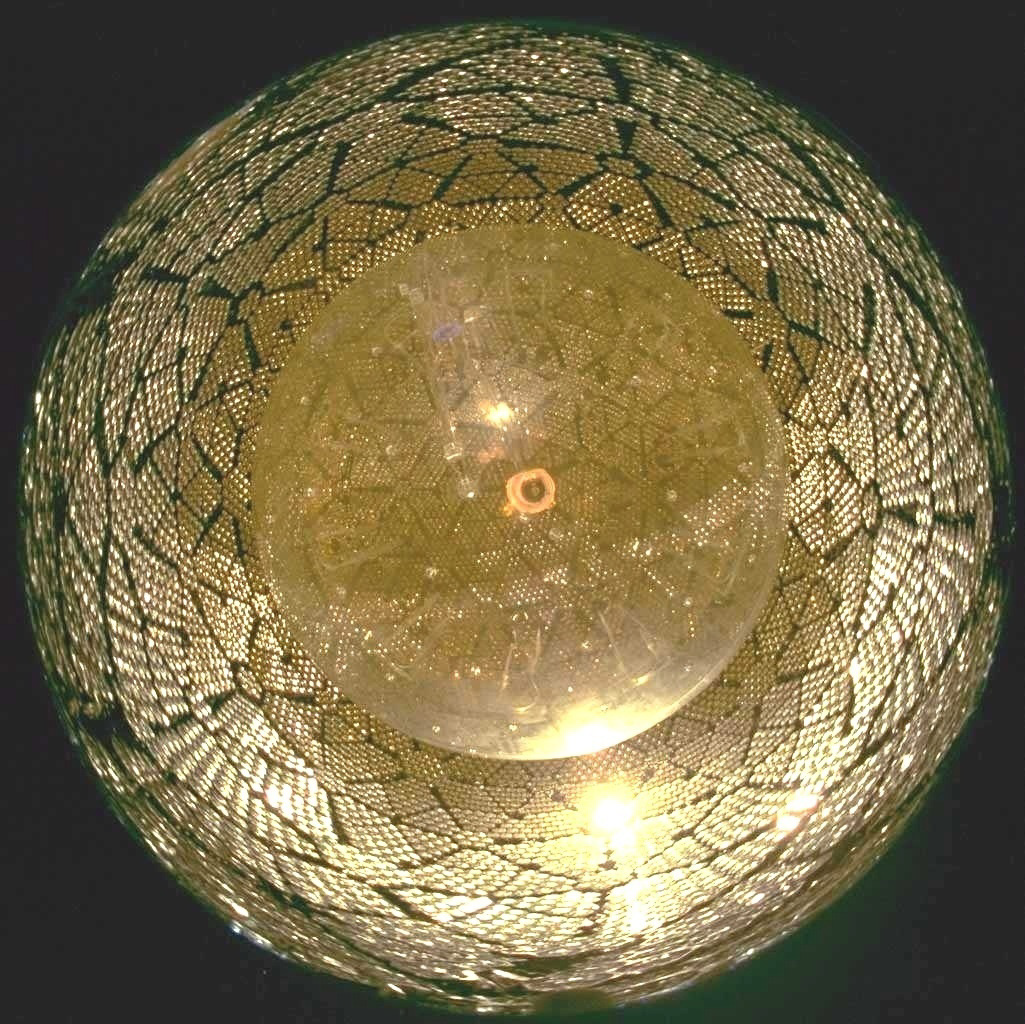
$$M_{Pl} = M_s (M_s R)^{n/2}$$

would mean that M_{Pl} results from a false extrapolation



Gravity's true scale could be near EW scale. (Subversive idea)


$M^2 = M^{n+2} R^n$
Amor



ν_{solar} News

$$\phi^{\text{CC}}_{\text{SNO}}(\nu_e) = 1.75 \pm 0.07\ (\text{stat.})^{+0.12}_{-0.11}\ (\text{sys.}) \pm 0.05\ (\text{th.}) \times 10^6\ \text{cm}^{-2}\ \text{s}^{-1}$$

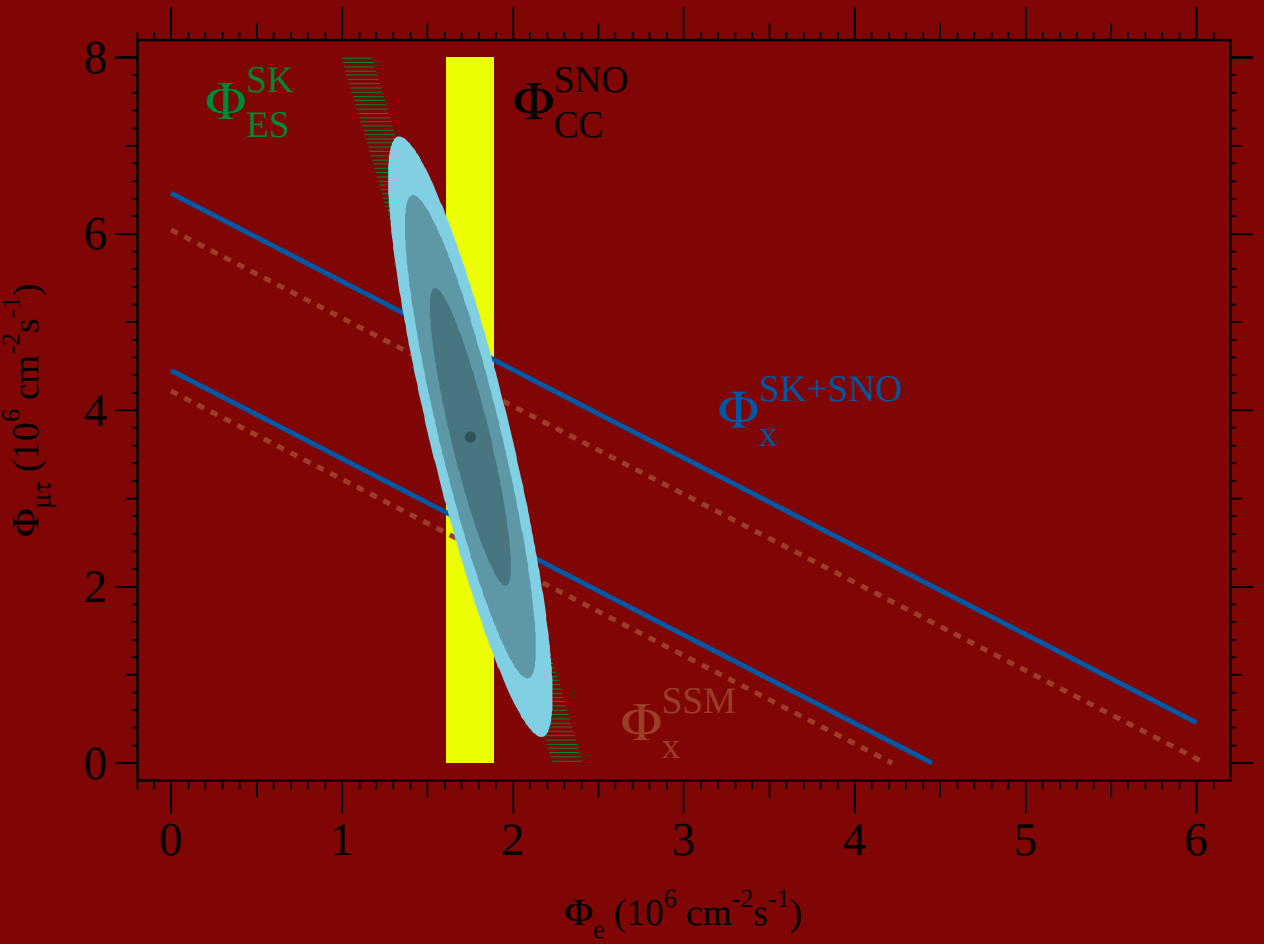
$$\phi^{\text{ES}}_{\text{SNO}}(\nu_x) = 2.39 \pm 0.0.34\ (\text{stat.})^{+0.16}_{-0.14}\ (\text{sys.}) \times 10^6\ \text{cm}^{-2}\ \text{s}^{-1}$$

$$\phi^{\text{ES}}_{\text{Super-K}}(\nu_x) = 2.32 \pm 0.03\ (\text{stat.})^{+0.08}_{-0.07}\ (\text{sys.}) \times 10^6\ \text{cm}^{-2}\ \text{s}^{-1}$$

$$\phi^{\text{ES}}_{\text{Super-K}}(\nu_x) - \phi^{\text{CC}}_{\text{SNO}}(\nu_e) = 0.57 \pm 0.17 \times 10^6\ \text{cm}^{-2}\ \text{s}^{-1}$$

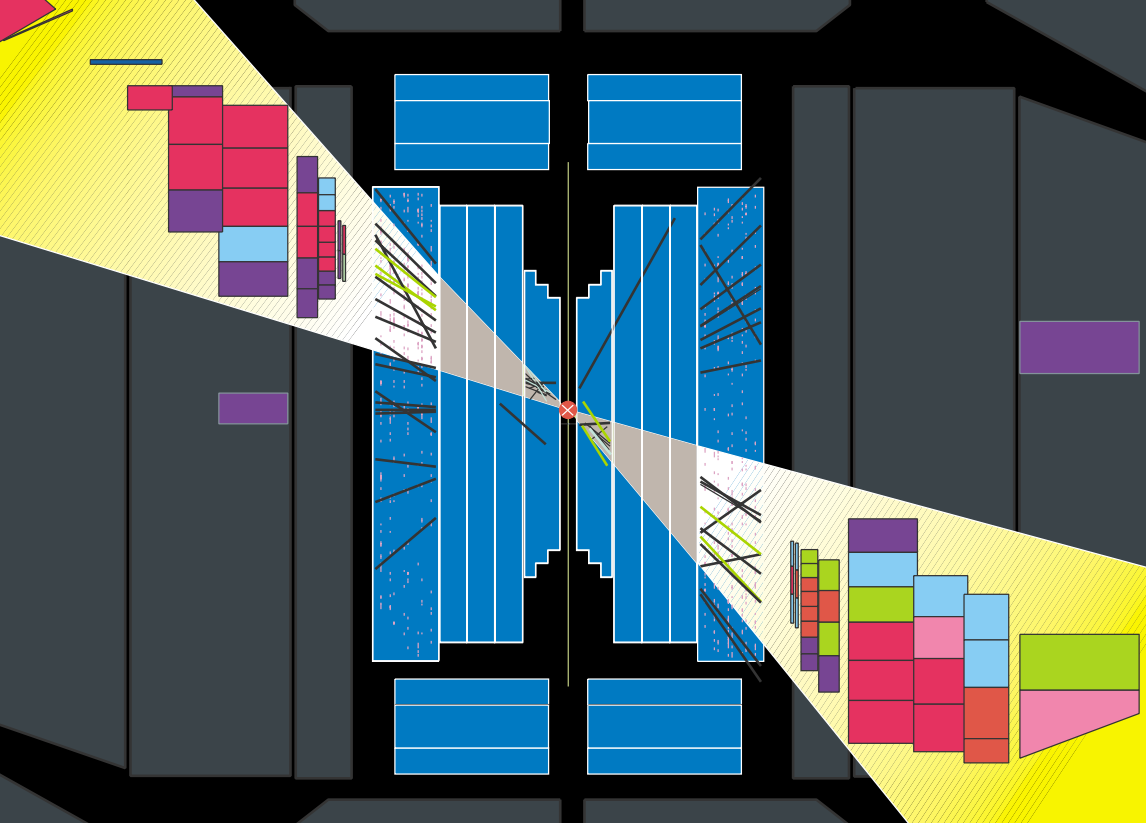
$$\boxed{\Longrightarrow \nu_\mu \text{ and } \nu_\tau \text{ arrive at Earth (at } 3.3\sigma)}$$

Combined SNO + Super-K ^{8}B Neutrinos



$$\phi(\nu_{\mu\tau}) = 3.69 \pm 1.13 \times 10^6 \text{ cm}^{-2} \text{ s}^{-1}$$

$$\phi(\nu_{\text{active}}) = 5.44 \pm 0.99 \times 10^6 \text{ cm}^{-2} \text{ s}^{-1}$$



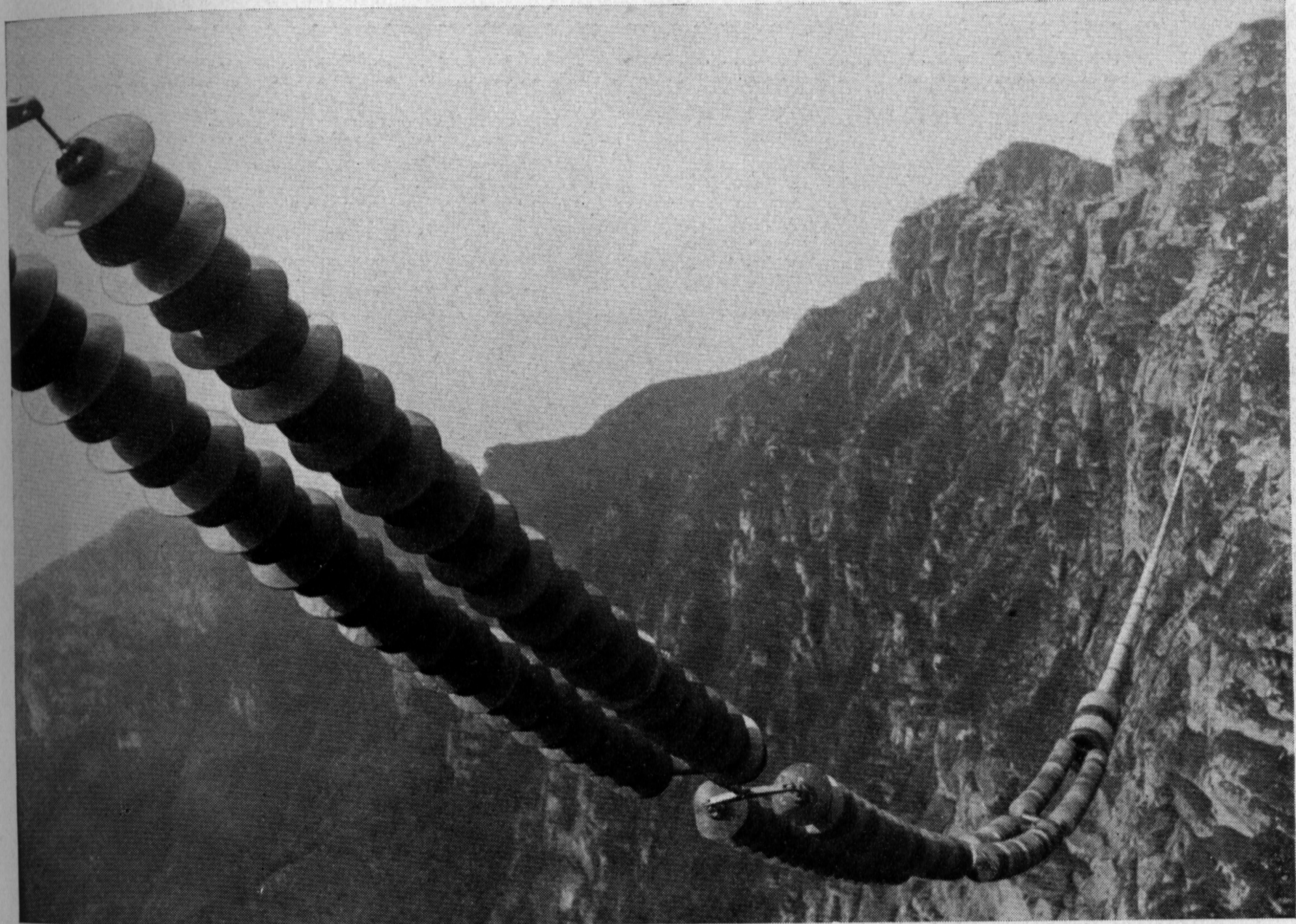


Fig. 3.
120 gliedrige Doppelkette aus Steatitmotorisolatoren.
Länge etwa 25 m, Gewicht der Kette etwa 2400 kg.

A Decade of Discovery Ahead

In the midst of a revolution in our conception of Nature, we deal with fundamental questions about our world, including

- Are the quarks and leptons elementary or composite?
- What are the symmetries of Nature, and how are they hidden from us?
- Are there new forms of matter, like the superpartners suggested by supersymmetry?
- Are there more fundamental forces?
- What makes an electron an electron and a top quark a top quark?
- What is the dimensionality of spacetime?

Nothing is too wonderful to be true,
if it be consistent with the laws of nature . . .
Experiment is the best test
Michael Faraday

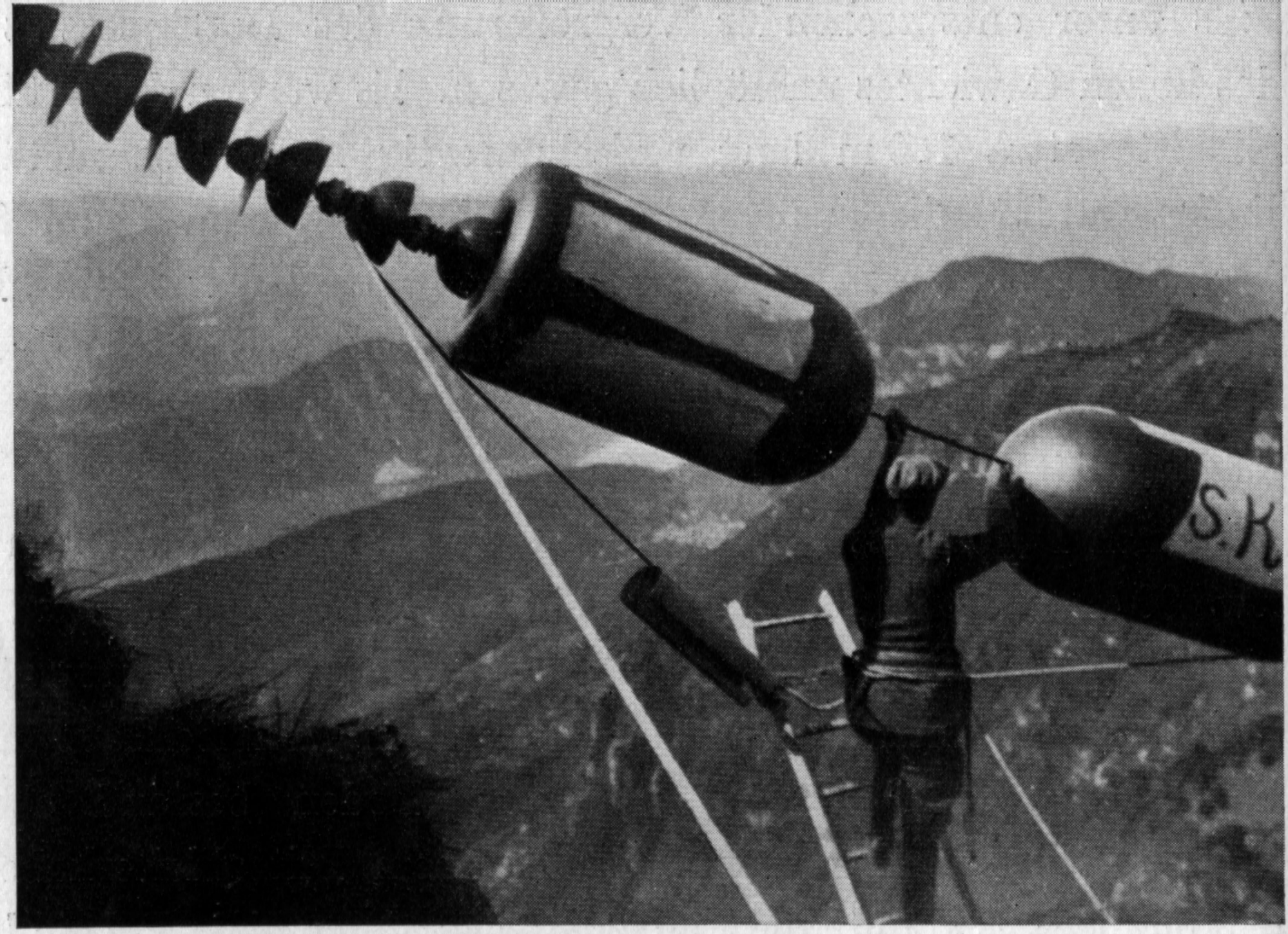


Fig. 2.
Montage der letzten Sprühschutzkörper. Durchmesser 80 cm.